EVALUATION OF INDUCTIVE VOLTAGE DIVIDERS AND 10 nF CAPACITORS IN A CAPACITANCE CALIBRATION METHOD

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Abstract

Researchers within the Quantum Electrical Metrology Division at the National Institute of Standards and Technology[3] (NIST) have implemented a calibration procedure for four-terminal-pair capacitance standards from 0.01 µF to 100 µF [1], [2]. This method depends on the accurate characterization of a 1 nF capacitor and an Inductive Voltage Divider (IVD) 1:10 ratio from 100 Hz to 100 kHz. This paper discusses a procedure that evaluates the IVD ratio and offers an enhancement over the current method. Also the evaluation of the 10 nF capacitor is presented and a measurement procedure modification is suggested that significantly improves the result.

Introduction

Ceramic capacitors are characterized using a capacitance scaling calibration procedure introduced in [3]. The capacitance scaling method depends on characterization of 100 pF and 1 nF capacitors that are evaluated using a network analyzer [4], [5].

There are four measurements in the capacitance scaling procedure necessary to calibrate an inductive voltage divider. First, the 100 pF capacitor is measured using an automatic capacitance bridge, producing C_{100pCB}. The next measurement is of the impedance of the 100 pF capacitor using an LCR meter with the inductive voltage divider in the circuit, giving $Z_{100pLCR}$. Next, the 1 nF standard is measured using the LCR meter, producing Z_{1nLCR}. Lastly, the automatic capacitance bridge is used to measure the 1 nF, giving C_{1nCB1}. The IVD ratio is then calculated using

$$Z_{100pCB} = \frac{1}{\omega C_{100pCB}} \ldots Z_{1nCB_1} = \frac{1}{\omega C_{1nCB_1}}$$

$$Z_{100pLCR} = IVD_{ratio} \frac{1}{\omega C_{100pCB}}$$

$$\frac{Z_{100pLCR}}{Z_{1nLCR}} = \frac{IVD_{ratio} \frac{1}{\omega C_{100pCB}}}{\frac{1}{\omega C_{1nCB_1}}} \rightarrow IVD_{ratio} = \frac{Z_{100pLCR}}{Z_{1nLCR}} \frac{C_{100pCB}}{C_{1nCB_1}}$$

Since the 1 nF and 100 pF capacitors have air dielectric, they do not exhibit significant dissipation factor over the frequency range of interest (100 Hz and 100 kHz). It is assumed that the impendence measured using the LCR meter and the capacitance ratio measured using the capacitance bridge, are related to the in-phase and quadrature IVD errors.

IVD Evaluation

The capacitance scaling method was implemented and tested over a period of time. The data collected at 1 kHz are presented in Table 1. Let us analyze the IVD measurement uncertainty. Since both measurements use the same instrument, systematic errors are canceled and only random errors influence the result. The LCR meter measures two very similar numerical values and the nonlinearity contribution is not significant, but it will be taken into account. The capacitance bridge measures two distinct values and additional uncertainty is added.

File name	IVD M	C100p/C1n	X100p/X1n
'3_25_5'	0.0999988	0.0999909	1.000079
'4_4_5'	0.0999995	0.0999905	1.00009
'5_24_5'	0.099999	0.0999883	1.000107
'5_25_5'	0.0999992	0.0999896	1.000096
'6_10_5'	0.0999996	0.099989	1.000106
'7_25_5'	0.0999995	0.0999885	1.00011
'7_25_5'	0.0999995	0.0999881	1.000114
'9_15_5'	0.0999983	0.0999889	1.000094
'9_16_5'	0.0999992	0.0999886	1.000106
'9_16_5'	0.0999993	0.0999891	1.000102
'10_28_5'	0.0999987	0.0999888	1.000099
'11_4_5'	0.0999988	0.0999883	1.000105
'11_8_ 5'	0.0999992	0.0999889	1.000102
'11_9_5'	0.0999991	0.0999886	1.000104
'11_10_5'	0.0999994	0.09999	1.000094
'11_14_5'	0.0999993	0.0999893	1.0001
'12_1_5'	0.0999965	0.0999896	1.000069
'12_2_5'	0.0999951	0.0999888	1.000063
'12_8_5'	0.0999993	0.0999894	1.000099
'12_8_5'	0.0999993	0.099989	1.000103
'12_13_5'	0.0999993	0.099988	1.000113
'12_20_5'	0.099999	0.0999883	1.000107
'12_22_5'	0.0999992	0.0999894	1.000097
'12_23_5'	0.0999993	0.099989	1.000102
AVERAGE	0.0999989	0.099989	1.000098
STD 10e-6	10.1	7.1	12.4

Table 1. Measurements related to IVD ratio evaluation. IVD M is the obtained IVD ratio. X100p/X1n is the ratio of impedances measured using the LCR meter. C100p/C1n is the ratio of capacitances measured using the capacitance bridge.

The impedances of the reference and test standards, measured with the LCR meter, are not independent variables, but rather, the ratio better represents of the measurement conditions. The same holds for the capacitance bridge measurements. The following formula demonstrates the relationship:

[3] Electronics and Electrical Engineering Laboratory, Technology Administration, U.S. Department of Commerce. Contribution of the U.S. Government. Not subject to copyright in the U.S.

$$\frac{\partial IVD_{ratioB}}{IVD_{ratioB}} = \sqrt{\left(\frac{\Delta_r\left(\frac{Z_{100pLCR}}{Z_{1nLCR}}\right)}{\frac{Z_{100pLCR}}{Z_{1nLCR}}}\right)^2 + \left(NL_{LCR}\right)^2 + \left(\frac{\Delta_r\left(\frac{C_{100pCB}}{C_{1nCB}}\right)}{\frac{C_{100pCB}}{C_{1nCB}}}\right)^2 + \left(NL_{CB}\right)^2}$$

The observed standard deviation for the impedance ratio measured with the LCR meter was 13 parts in 10^6 and the standard deviation of the capacitance ratio measured with the capacitance bridge was 7.5 parts in 10^6. Using the above formula to calculate the uncertainty of the IVD with nonlinearity errors for the LCR meter and the capacitance bridge of 1 part in 10^6 gives

$$\frac{\partial IVD_{ratio}}{IVD_{ratio}} = 10^{-6}\sqrt{13^2 + 1^2 + 7.5^2 + 1^2} = 15\_10^{-6}$$

The experimentally determined standard deviation of the IVD ratio is 10 parts in 10^6. The calculated uncertainty of 15 parts in 10^6 is higher compared to the obtained measurements. The reason is that in each measurement, the same set of capacitors is used and the characteristics of those devices are influenced in the same way by the environment so that the LCR meter and capacitance bridge readings reflect the same device and are not independent.

Inductive voltage dividers are in general very accurate and stable devices. The IVD used in the capacitance scaling apparatus is well designed and should not exhibit 10-15 parts in 10^6 variations in the ratio. These fluctuations are related to the measurement process in which capacitors demonstrate environmental dependence and LCR meter measurements have very high variations (up to 80 parts in 10^6).

The fluctuations in the IVD ratio directly influence all other capacitance scaling measurements. We propose an improved method of evaluating the IVD ratio using a 'running' average. The data pool collected provides a good estimate of the average ratio and it could be used in the subsequent measurements. At the same time new ratios are measured, added to the pool and in that way, update the data set. This approach will be tested and the results will be presented at the conference.

Measuring 10 nF capacitor

The next step in the capacitance scaling procedure finds the impedance of a 10 nF capacitor. A 1 nF capacitor is measured using the capacitance bridge, C_{1nCB2}, and using the LCR meter and IVD, Z_{1nLCR2}. Then, a 10 nF capacitor (DUT) is measured using the LCR meter, Z_{10nLCR}. The derivation of the method follows.

$$Z_{10nLCR} = Z_{DUT10n}$$

$$Z_{1nLCR_2} = IVD_{ratio}\frac{1}{\omega C_{1nCB_2}}$$

$$\frac{Z_{1nLCR_2}}{Z_{10nLCR}} = \frac{IVD_{ratio}\frac{1}{\omega C_{1nCB_2}}}{Z_{DUT10n}}$$

$$Z_{DUT10n} = \frac{Z_{10nLCR}}{Z_{1nLCR_2}} IVD_{ratio}\frac{1}{\omega C_{1nCB_2}}$$

So, the uncertainty associated with this set of measurements is:

$$\frac{\partial Z_{DUT10n}}{Z_{DUT10n}} = \sqrt{\left(\frac{\partial IVD_{ratio}}{IVD_{ratio}}\right)^2 + \left(\frac{\Delta_r\frac{Z_{10nLCR}}{Z_{1nLCR_2}}}{\frac{Z_{10nLCR}}{Z_{1nLCR_2}}}\right)^2 + \left(NL_{LCR}\right)^2 + \left(\frac{\Delta_{r1nCB_2}}{C_{1nCB_2}}\right)^2 + \left(\frac{\Delta_{S1nCB_2}}{C_{1nCB_2}}\right)^2}$$

Note that the measurement of C_{1nCB2} has both Type-A and Type-B components of the error since we do not have the matching measurement using the capacitance bridge. The specifications for the capacitance bridge list absolute uncertainty to be 5 parts in 10^6. Numerical estimation of the uncertainty of the 1 nF standard impedance follows;

$$\frac{\partial Z_{DUT10n}}{Z_{DUT10n}} = 10^{-6}\sqrt{1.2^2 + 10^2 + 5^2} = 12\_10^{-6}$$

The goal of this measurement procedure is to estimate the capacitance and dissipation factor for a given capacitor. The actual fluctuations of the measured capacitance of a 10 nF standard were on the order of 9 parts in 10^6, so that this analysis matches the measurements.

Note that the 1 nF capacitor is measured twice using the capacitance bridge: once in the IVD calibration procedure and once in the 10 nF scaling procedure. These two measurements are performed on the same device about 10 minutes apart. We will take the 1 nF capacitor measurement from the IVD procedure and use the same result when estimating the impedance of a 10 nF capacitor.

$$Z_{DUT10n} = \frac{Z_{100pLCR}}{Z_{1nLCR_1}}\frac{C_{100pCB}}{C_{1nCB_1}}\frac{Z_{10nLCR}}{Z_{1nLCR_2}}\frac{1}{\omega C_{1nCB_1}} = IVD_{ratio}\frac{Z_{10nLCR}}{Z_{1nLCR_2}}\frac{1}{\omega C_{1nCB_1}}$$

These calculations give the estimations of the capacitance with a standard deviation of 2 parts in 10^6 (see Figure 1). This is a significant improvement over the results obtained in the current procedure measuring the 1 nF standard twice using the capacitance bridge.

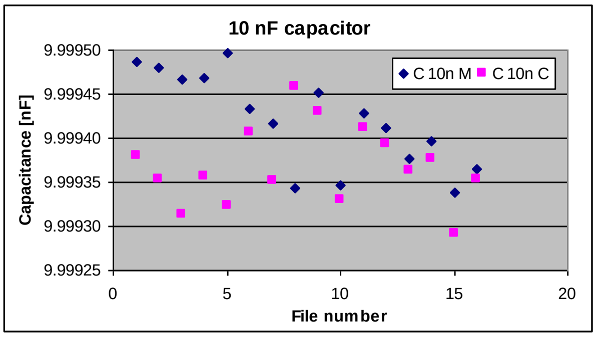

Figure1. Method comparison. The 'C 10n M' points show the results obtained using the current method. The 'C 10n C' points are the results obtained using the proposed method where the 1 nF capacitor is measured only once.

References

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